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FINAL REPORT
of
A RESEARCH PROGRAM
on
The Design, Planning and Control of Robotic Systems in Space

July 22, 1994 to September 30, 1996

GRANT NUMBER: NAG 1-1637 (CONT. OF NAG 1-801)



Submitted to
Automation Research Branch
National Aeronautics and Space Administration
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EXECUTIVE SUMMARY AND INTRODUCTION

A. Program Motivation and Objectives

In the future, robotic systems will be expected to perform important tasks in space, in orbit and in planetary exploration. In orbit, current technology requires that tasks such as the repair, construction and maintenance of space stations and satellites be performed by astronaut Extra Vehicular Activity (EVA). Eliminating the need for astronaut EVA through the use of space manipulators would greatly reduce both mission costs and hazards to astronauts. In planetary exploration, cost and logistical considerations clearly make the use of autonomous and telerobotic systems also very attractive, even in cases where an astronaut explorer might be in the area. However, such applications introduce a number of technical problems not found in conventional earth-bound industrial robots. To design useful and practical systems to meet the needs of future space missions, substantial technical development is required, including in the areas of the design, control and planning.

The objectives of this research program were to develop such design paradigms and control and planning algorithms to enable future space robotic systems to meet their proposed mission objectives. The underlying intellectual focus of the program is to construct a set of integrated design, planning and control techniques based on an understanding of the fundamental mechanics of space robotic systems. This work was to build upon the results obtained in our previous research in this area supported by NASA Langley Research Center in which we have made important contributions to the area of space robotics.

B. Accomplishments

This program was proposed and accepted as a three year research program, a period of time necessary to make the type of fundamental developments to make a significant contributions to space robotics. Unfortunately, less than a year into the program it became clear that the NASA Langley Research Center would be forced by budgetary constraints to essentially leave this area of research. As a result, the total funding we received under this grant represented approximately one year of the original, proposed and approved, funding. For some time, there was substantial uncertainty that even this very reduced level of funding would be provided. The spending of the reduced available funds was spread just over two years to provide the support to permit the MS students who had joined the program to receive their master's degree and terminate their studies in this area.

Because of the funding uncertainties and levels provided, the scope of the work was substantially reduced from the proposed level. Our work mainly focused on completing and documenting our research. Our previous NASA sponsored work had produced a number of new and important results in the area of space robotics. Significant theoretical results have been obtained that contribute to our understanding of the fundamental nature of space robotic systems. During this shortened and greatly reduced funded program our work focused on extending and experimentally validating some of the algorithms we had developed during our previous work. The work did not attempt to begin development of new basic approaches and concepts.

In a related matter, we had been working on a NASA funded IN-STEP Program with Martin Marietta, The University of Puerto Rico and NASA Langley to prepare a flight robotics experiment that would test our theories on the control and planning of flexibly supported space robotic manipulators. We were competing with approximately six other teams. It was expected that one or two of these teams would be selected to design and build a flight experiment. At the completion of the Phase A study NASA chose not to select any of these programs for Phase B. It is not clear that the Phase A study results were ever technically evaluated.

During this period we continued to make important contributions to the international space robotics research. We have had several international researchers, sponsored by their home countries-- Canada, Italy, France, Germany, and Japan--working in our laboratory. These researchers have learned a great deal and they have also made very meaningful contributions to the technical objectives of our program.

In summary, the program yielded important technical results in the area of the dynamics and control of manipulators in space. The work has also had an important influence both here in the United States and abroad. The technical papers and student theses that document the contributions of the program during this period are listed in the following section.

THESES, PAPERS, LECTURES AND VISITING RESEARCHERS

Papers and theses written, presented or published during the current three year period (7/94 to 9/96) are listed in this section.

A. Student Theses

During this period, the program has given non-degree research opportunities to 3 undergraduates under MIT's Undergraduate Research Opportunity Program (UROP).

In addition, the following students who have contributed to this program, have completed their degrees and written the following theses:

1. Bachelors Theses

Student	Thesis Title	Date
Thomas, K.	"Design of the Supporting Structure for a Laboratory Long Reach Manipulator System Using Finite Element Analysis"	4/95
Ford, S.	"An In Situ Keel deformation Metrology System for the USS Constitution"	6/95
Raju, V.	"Design of an Experimental Systems for Modular Robotic Systems"	6/96

2. Masters Theses

Student	Thesis Title	Date
Rutman, N.	"Automated Design of Modular Field Robots"	6/95
Cole, J.	"Rapid Generation of Motion Plans for Modular Robotic Systems"	6/95

3. Ph.D. Theses

None

B. Research Affiliates

During this period the following visiting researchers and researchers in residence have also contributed to our program:

Pisoni, Attilio Carlo
Ancona University
Ancona, Italy

Dr. Mavroidis, Constantinos
University of Paris IV
Paris, France

Prof. Yoshida, Kazuya
Tokyo Institute of Technology
Tokyo, Japan

Dr. Rudolph, S.
Stuttgart University
Stuttgart, Germany

Dr. Guillaume Morel
The CNRS Robotics Laboratory of Paris
Paris, France

Dr. Phillipe Bidaud
The CNRS Robotics Laboratory of Paris
Paris, France

Dr. Guang Jun Liu
University of Toronto
Toronto, Canada

C. Period Technical and Professional Papers

During this period the following technical and professional paper were published or accepted for publication.

Dubowsky, S., Durfee, W., Corrigan, T., Kuklinski, A. and Muller, U., "A Laboratory Test Bed For Space Robotics: The VEST Mod II, *Proceedings of the IROS '94 IEEE/RSJ/GI International Conference on Intelligent Robots and Systems-Advanced Robotic Systems and the Real World*, München, Germany, September 12-16, 1994 . Also published in *Intelligent Robots and Systems*, by Elsevier Science, Amsterdam, pp. 463-475

Corrigan, T. and Dubowsky, S., "Emulating Micro-Gravity in Laboratory Studies of Space Robotics," *Proceedings of the 23rd ASME Mechanisms Conference*, MN, Sept. 1994 .

Dubowsky, S., Durfee, W., Kuklinski, A., Müller, U., Paul, I. and Pennington, J., "The Design and Implementation of a Laboratory Test Bed for Space Robotics: The VES MOD II," *Proceedings of the 23rd ASME Mechanisms Conference* , Minneapolis, Sept, 1994. Also accepted *ASME Journal of Mechanical Design*,

Dubowsky, S., Moore, C., and Sunada, C., "On the Design and Task Planning of Power Efficient Field Robotic Systems," *Proceedings of ANS 6th Topical Meeting on Robotics and Remote Systems and ANS Transaction.*, Monterey, California, Feb. 5-10, 1995, pp. 501-508.

Mavroidis, C., Rowe, P. and Dubowsky, S., "Inferred End Point Control of Long Reach Manipulators", *Pro. IEEE International Conference on Intelligent Robots and Systems, IROS 95*, Pittsburgh, PA, August 1995.

Cole, J., Dubowsky, S., Rutman, N. and Sunada, C. "The Application of Advanced Robotics and Sensor Technologies to the Preservation of the USS Constitution" *Proceedings of the Conference on the Technical Aspects of Maintaining, Repairing and Preserving Historically Significant Ships*, Sept., 1994, Boston, MA. .

Pisoni, A.C., Santolini, C. and Dubowsky, S. "Displacements in a Vibrating Body By Strain Gauge Measurements" *Proc. 3th International Modal Analysis Conference*, February 13-16, 1995, Nashville, TN .

Mavroidis, C., Rowe, P. and Dubowsky, S., "The Control of Elastically Mounted Manipulator Systems" *Proc. Ninth World Congress on the Theory of Machines and Mechanisms*, September 1-2, 1995, Milano, Italy,.

Dubowsky, S. "Dealing with Vibrations in the Deployment Structures of Space Robotic Systems" *Proceedings of the 5th International Conference on Adaptive Structures*, Sendai, Japan, De. 1994. (Keynote).

Yoshida, K., Mavroidis, C. and Dubowsky, S. "Experimental Research on Impact Dynamics of Spaceborne Manipulator Systems" *Proceeding of the 4th International Symposium on Experimental Robotics*, June 30-July 2, 1995, Stanford, California, pp. 271-277.

Farritor, S., Dubowsky, Rutman, N. and Cole, J. "A Systems Level Modular Design Approach To Field Robotics," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, April 24-27, 1996.

Morel , G. and Dubowsky, S., "The Precise Control Of Manipulators With Joint Friction: A Base Force/Torque Sensor Method," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, April 24-27, 1996.

Torres, M., A., Dubowsky, S., Pisoni, A. C., "Vibration Control of Deployment Structures of Long-Reach Space Manipulators: The P-PED Method," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, April 24-27, 1996.

Yoshida, K., Mavroidis, C., and Dubowsky, S., " Impact Dynamics of Space Long Reach Manipulators," *Proceedings 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, Apr., 1996.

Yoshida, K., Mavroidis, C., and Dubowsky, S., " Impact Dynamics of Space Manipulators Mounted on a Flexible Structure," *Proceedings of the 3rd International Conference on Dynamics and Control of Structures in Space*, London, England, May 27-31, 1996.

Morel, G. and Dubowsky, S., "High Performance Control of Manipulators Using Base Force/Torque Sensing," *Proceedings of XI CISM-IFTOMM Symposium on Theory and Practice of Robots and Manipulators (ROMANSY '96)*, Udine, Italy, July 1-4, 1996.

Mavroidis, C., Dubowsky, S. and Thomas, K., "Optimal Sensor Location in the Motion Control of Flexibly Supported Long Reach Manipulators," *Proc. 1996 ASME Mechanisms Conference*, Irvine, CA, Aug, 1996.

Farritor, S. and Dubowsky, S., "On the Design of Rapidly Deployable Field Robotic Systems," *Proceedings of the 1996 ASME Design Methodology Conference*, Irvine, CA, August 19-22, 1996.

Torres, M. Dubowsky, S., Corrigan, T. and Pisoni, A. C., "The Coupling Map Method for Path Planning of Long Reach Space Robotics Systems with Experimental Evaluation", *Accepted IEEE Transactions on Robotics and Automation*.

Invited Lectures

As part of our technology transfer efforts Professor Dubowsky gave the following invited lectures and seminars during this period related to our NASA sponsored results.

September 1994, "The Application of Advanced Robotics and Sensor Technologies to the Preservation of the USS Constitution," Boston National Historical Park, Charlestown Navy Yard, Charlestown, MA.

October 1994, "Space Robotics Technology and its Applications to the Preservation of the USS Constitution," University of Wisconsin-Madison, Dept. of Mechanical Engineering, Madison, WI.

November 1994, "The Control for Mobile Multi-Limbed Robots", University of B.C., Vancouver, Canada.

November 1994, "On the Dynamics and Control of Space Robotic Systems," Simon Fraser University, School of Engineering Science, Burnaby, B.C., Canada.

November 1994, "On the Dynamics and Control of Long Reach Space Robotics Systems", University of Victoria, Vancouver, Canada.

December, 1994, "Dealing with Vibrations in the Deployment Structures of Space Robotic Systems" *Proceedings of the 5th International Conference on Adaptive Structures*, Sendai, Japan.

December 1994, "On the Dynamics and Control of Space Robots," Tokyo Institute of Technology, Japan.

December 1994, "On the Dynamics and Control of Space Robots," Kawasaki Heavy Industries, Japan.

January 1995, "On the Dynamics and Control of Long Reach Robotic Systems, with Application to Space Station Alpha and the USS Constitution", UCLA, Dept. of Mechanical, Aerospace and Nuclear Engineering, Los Angeles, CA.

February, 1995, On the Design of Mobile Telerobotic Systems in Unstructured Environments, with Application to the Restoration and Preservation of Historic and Artistic Treasures and Sites, American Nuclear Society Sixth Meeting on Robotics, Monterey, CA, Feb, 1995, (Keynote Address).

October, 1995, "The Dynamics and Control of Long Reach Manipulators," Laboratoire de Mécanique des Solides, Université de Poitiers, Poitiers, France.

September-November 1995, Series of six seminars on "The Dynamics and Control of Robotic Manipulators," Robotics Laboratory of Paris, Université Pierre et Marie Curie (Paris VI).

January, 1996, The Modular Design of Robotic Systems Using Genetic Algorithms," Laboratory of Fundamental Computer Science and Artificial Intelligence, INRIA Rhône Alps, Grenoble, France.

March, 1996, The Design of Rapidly Deployable Systems Using Modular Methodology, The Engineering Design Center, Engineering Department, Cambridge University, Cambridge, England.

June 1996, On the State-of-the Art of Robotic Systems, Sandia National Laboratories, Albuquerque, NM.

A PROPOSAL FOR A THREE YEAR RESEARCH PROGRAM
on
The Design, Planning and Control of Robotic Systems in Space
(June 1, 1994 to May 31, 1997)



Submitted

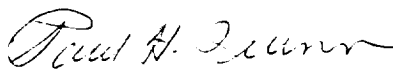
April 25, 1994

to

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I. EXECUTIVE SUMMARY AND INTRODUCTION

A. Motivation and Objectives

In the future, robotic systems will be expected to perform important tasks in space, in orbit and in planetary exploration. In orbit, current technology requires that tasks such as the repair, construction and maintenance of space stations and satellites be performed by astronaut Extra Vehicular Activity (EVA). Eliminating the need for astronaut EVA through the use of space manipulators would greatly reduce both mission costs and hazards to astronauts. In planetary exploration, cost and logistical considerations clearly make the use of autonomous and telerobotic systems also very attractive, even in cases where an astronaut explorer might be in the area.

However, such applications introduce a number of technical problems not found in conventional earth-bound industrial robots. To design useful and practical systems to meet the needs of future space missions, substantial technical development is required, including in the areas of the design, control and planning. The objective of this proposed three-year research program is to develop such design paradigms and control and planning algorithms to enable future space robotic systems to meet their proposed mission objectives. The underlying intellectual focus of the program is to construct a set of integrated design, planning and control techniques based on an understanding of the fundamental mechanics of space robotic systems. This work will build upon the results obtained in a currently concluding research program in this area supported by NASA Langley Research Center in which we have made important engineering contributions to the area of space robotics. These contributions are briefly outlined below.

B. Accomplishments of Our Past Work

Our NASA sponsored work to date has produced some new and important results in the area of space robotics. Significant theoretical results have been obtained that contribute to our understanding of the fundamental nature of space robotic systems. Also new effective planning and control algorithms for these systems have been developed. Finally we have developed unique, and very useful, simulation and experimental tools for evaluating the dynamic performance of space robotic systems. Most notable is the successful completion of two new VES systems (MOD II), one for our laboratory and one for use at NASA Langley. It is interesting that at least one copy of this system has appeared in an industrial laboratory in Japan. We are also pleased that we were invited to contribute the keynote paper in the area of dynamics and

control for the recent special issue on space robotics of the *IEEE Journal of Robotics and Automation* [16]. Bracketed numbers refer to papers listed in Section V.

The program has also been making a significant impact outside the academic domain. We have been working with Martin Marietta Aerospace, Denver, to evaluate our *flexible base* planning and control algorithms using their experimental facilities. This work has contributed to a successful proposal for Phase A - IN-STEP Program about to begin, with the Martin Marietta, MIT, The University of Puerto Rico and NASA Langley as team members. We were also invited to have worked with Goddard Flight Center preparing their IN-STEP proposal for a flight robotic system that would use our *free-flying* robot control algorithms. These activities are a strong indication that our studies have been yielding important and potentially useful results in space robotics.

In addition, our results have had an impact on the civilian sector. We have been working with the Getty Conservation Institute, a branch of the J. Paul Getty Foundation, to apply recent advances in robotics to the conservation, preservation and restoration of archeological and architectural treasures. We have now identified the preservation of the USS Constitution (*Old Ironsides*) as a meaningful demonstration project for this research. We are currently defining, with the Office of the Naval Historian, who is charged by Congress with the care and preservation of this national treasure, the technical and preservation objectives of a robotic inspection robot for the ship. As discussed in Section III, the USS Constitution will also play an important role as a testbed for the technology that will be developed in our proposed research program.

Most importantly, the program has contributed to the education of a noteworthy number of students and produced substantial scholarly and professional publications. Also, we have had a number of international researchers, sponsored by their home countries--Italy, France, Germany, and Japan--working in our laboratory. These researchers have learned a great deal and they have also made very meaningful contributions to the technical objectives of our program. We also continue to have regular exchanges in our long standing and very successful relationship with the Laboratoire De Robotique De Paris. We expect these to continue under this proposed program. Through these exchanges, invited lectures and publications, this program is having an important impact on the development of space robotics internationally.

In summary, the program has been yielding important technical results in the area of the dynamics and control of manipulators in space. The work is now having an important influence both here in the United States and abroad. The technical papers

and student theses that document the contributions of the program during the past three years are listed in Section V of this proposal.

C. Proposed Research

Our earliest work focused on solving the planning and control problems of free-flying space robotic systems. To solve these problems we have developed new modeling tools, unique and effective planning and control algorithms, and experimental systems. These contributions were based on developing a fundamental understanding of the physics of these systems. However, important and fundamental control problems remain unsolved. For example, the weight limitation placed on space systems will require that these systems operate while being carried by highly flexible deployable structures, such as the configuration that has been proposed for the space station. Figure 1 shows for a highly idealized version of this system concept.

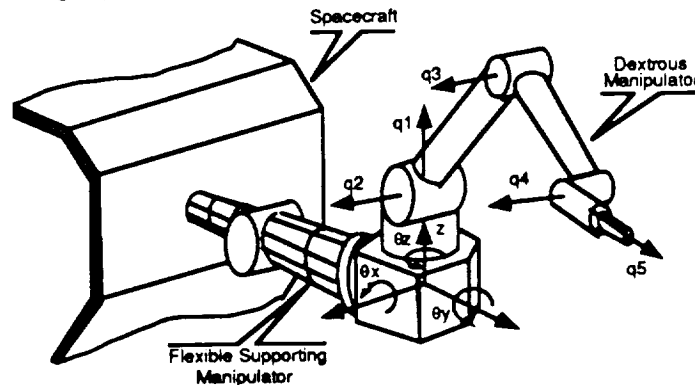


Figure 1: A Space Robotic System Concept

This flexibility would degrade system accuracy and could even make the system unstable. We have proposed new planning and control techniques that can minimize and accommodate the effects of this flexibility [21, 24, 30]. However substantial research is required before these algorithms can be applied to realistically complex systems. For example, the successful control of such a system depends upon the ability to place the sensors at the most appropriate locations on the structure and to build sufficiently accurate elasto-dynamic models of the supporting structure. Fundamental questions, such as "where the sensors should be located?" and "how accurate the models need to be?" remain unanswered. These would be addressed in our research.

Other research in the program is motivated by expectations that some future space robotic systems will probably be highly redundant, multi-limbed systems performing manipulation (both force and motion) and mobility tasks while they interact with their tasks and environment. Applications include a robotic maintenance system climbing

over the exterior of the space station and a planetary system exploring rough terrain while gathering heavy rock samples. Such multi-limbed systems in unstructured environments present some very challenging design, control and planning problems. These systems will often need to be self-contained. For example, they will need to carry their own power supplies and perform most control computations with relatively small on-board computers. Hence, they will need to be designed to be power efficient and to act to conserve power. Its control and planning algorithms cannot be computationally intensive. Meeting these objectives will require new design, planning and control methods.

In this proposed three-year research program, our work will focus on developing the fundamental concepts required to solve these problems. As with our previous contributions, our work will include studying the fundamental mechanics behind the problems, analytically developing solutions to these problems, studying the effectiveness of these solutions using simulations, and finally, verifying the results of the research experimentally.

This work will build upon the progress and results we have obtained during our currently concluding NASA sponsored research program. During this work we have developed some powerful tools for studying robotic systems. These tools include our dynamic simulations of space robotic systems, their associated computer graphics interfaces, and our experimental facilities for evaluating control algorithms for robotic systems, most notably our Vehicle Emulator System (VES), MOD II.

II. A BRIEF REVIEW OF RECENT TECHNICAL ACCOMPLISHMENTS

A. Fundamental Studies

1. Free-flying and free-floating space robotic systems

Our earliest space robotics research focused on understanding the fundamental nature of the dynamics and control of free-flying and free-floating robotic systems. It has resulted in important contributions to the understanding the behavior of these systems.

The results of this work include the following major theoretical milestones for free-flying and free-floating space robotics:

- The Virtual Manipulator.
- A theory describing the fundamental nature of control algorithms for free-flying and free-floating robotic systems.
- The discovery of performance degrading Dynamic Singularities in space robots.
- The Disturbance Map to extend the useful on-orbit life of free-flying space robots.
- The development of optimal control methods for free-flying space robots to prevent attitude control system reaction jet and reaction wheel saturation.

The algorithms we have developed, from the understanding given by our basic research, contribute to making possible the effective design, control and operation of free-flying and free-floating space systems. This is an important enabling technology base for the support of future flight programs of free-flying and free-floating robotic systems. A more detailed description of this work is contained in our prior grant progress reports and is documented in the papers listed in Section V of this proposal. Paper [16] contains a quite readable summary of many of these results.

2. Flexibly supported manipulator systems

More recently, we have studied robotic systems supported by structures with significant flexibility. The first work in this area treated manipulators mounted on vehicles, as might be used in planetary exploration [13]. We developed, and demonstrated in the laboratory using the VES, a technique to achieve fine manipulator performance in spite of vehicle motions, called Inferred Jacobian Transpose Control [20, 22, 30].

This method is directly applicable to such important space applications as the problems of a fine pointing-controller for a communications antenna on a lunar surface vehicle. It

could also be used in non-space applications such as environmental restoration and infrastructure inspection systems.

This work has now been extended to space manipulators mounted on very flexible structures, such as the SPDM carried by the SSRMS, or a flexibly mounted DOSS system. See Figure 1 for a simple example. This control method can be integrated with our Coupling Map planning method to plan and control graceful motions for these systems [21,24]. It can also be used with our P-PED control technique to damp out unwanted vibrations using the manipulator's control system.

All of these techniques have been demonstrated in the laboratory at MIT and at Martin Marietta, Denver, and are now being considered by the INSTEP Program for in-orbit demonstration and study. This technology is also important for non-space long reach manipulator systems that could be used for such applications as the inspection and repair of high tension electrical transmission lines and towers.

3. The force and motion control of multi-limbed mobile robotic systems

In this work we have considered the fundamental mechanics of multi-limbed systems interacting with their environment. The results have been the development of two new planning methods for such systems:

- The Force Workspace Method [12, 14, 18]
- The Power Map Approach [29]

The Force Workspace Method enables a system to be designed and its actions planned so that as it moves with large motions and within the constraints imposed by its capabilities, task and the environment. These constraints are treated in a consistent manner. The Power Map Approach extends this method to finding power efficient designs and actions. Such power efficient designs and plans are important for self-contained field systems such as planetary explorers.

We have also developed a method for controlling the motion of such systems and their interactive forces with the environment and tasks. This method is called Coordinated Jacobian Transpose Control [25].

This work has important potential application to a number of field space missions--including planetary exploration--and non-space field missions--such as the inspection

and maintenance of civil engineering structures. In our studies we have been considering a dual use application in the area of the restoration and preservation of archeological, historic, and architectural monuments and sites. As discussed above, we have been working closely with the Naval Historian responsible for the restoration and preservation of the *USS Constitution*.

B. Simulation Software and Experimental Systems Developed

1. Simulation Software

In our work during this period we have created and upgraded several of our most significant software tools for space robotic systems, including the FLEXARM III and RiBs simulation software packages for flexible and rigid space robotic systems.

It should be noted that the RiBs Program for the dynamic simulation of rigid robotic systems has now been used in approximately 4 Ph.D. theses, 6 Masters thesis and 5 BS theses. It has also been transferred to NASA Langley, the Italian Space Agency and one industrial firm. The FLEXARM III software for modeling the dynamics of flexible systems has been used in approximately 3 Ph.D. theses, 2 Masters Thesis and it has been transferred to three industrial firms.

2. Experimental Systems

We have also created experimental methods for studying the dynamic behavior of space robots and their control systems in the laboratory. Most significantly we have completed two VES MOD II vehicle emulation systems [26], see Figure 2.

We have also developed and demonstrated the theory, algorithms and software to perform very high quality micro-gravity emulation in the laboratory using the VES hardware [27]. It should also be noted that a second VES II is now at NASA Langley Research Center so that cooperative research can be performed by MIT and NASA. In addition, we are aware of at least one version of the VES having been constructed abroad.

During this period we have also designed and fabricated two new experimental systems: the Shaky system [24], for studying flexibly supported systems, and the LIBRA system [25], a three legged climbing robot.

LIBRA is a multi-limbed robotic device, used for experimentally testing our Force Workspace planning technology and Coordinated Jacobian Transpose Control method. It has been designed to climb between two vertical walls by pushing against the wall to create sufficient friction to keep it from slipping downward.

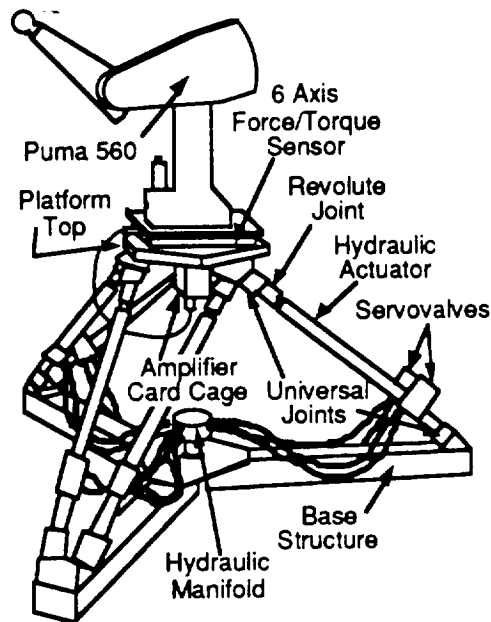


Figure 2. VES MOD II Experimental System

Shaky is a simple two-link manipulator mounted on a highly flexible beam-like base. It is being used to test our Coupling Map, P-PED and Inferred Jacobian Transpose Control algorithms. Both of these systems are controlled with our VME bus/PMAC control system. They also use common design actuators and encoder assemblies donated by their manufacturer. To keep costs low, these systems use common power electronics, designed and fabricated by our students.

III. A DESCRIPTION OF THE PROPOSED RESEARCH

A. Fundamental Research Studies

In our fundamental studies we will continue to develop new technology for space robotic systems based on a solid understanding of the physics of these systems. To some degree, the topics addressed will try to be responsive to NASA's needs by studying the underlying design, dynamics and control issues that are raised by possible future space mission scenarios as they develop. Our work will initially focus on the following three main areas.

1. The control of flexibly supported manipulator systems

Algorithms for controlling flexibly supported multiple arm manipulators, such as the SPDM carried by the SSRMS, or a flexibly mounted DOSS system, with limited sensing will be developed. This work will study the use of easily measured strain information from the supporting structure, instead of traditionally required end-point measurements, to achieve effective end-point control. It would build upon very promising preliminary results we have obtained with this approach for a relatively simple planar system [30]. The research issues to be addressed include:

- The development of structural models of the supporting systems, appropriate for real-time control.
- Optimal sensor placement.
- The effects of dynamic interactions of the permitted ranges of motion -- the dynamic workspace.

Simulations would be done using the FLEXARM III program and initial real-time models for control would be based on Component Mode Synthesis (CMS) methods. The results would first be experimentally verified using the VES refitted with a pair of PUMA 250 manipulators currently available for this research. These manipulators would then be mounted on a spatial light-weight instrumented structure that we will fabricate for this purpose, called Shaky II. This work would also have direct application to civilian robotics, such as long vertical reach systems for power line maintenance or mast inspection on the *USS Constitution*. It would also support our INSTEP efforts and the DOSS program.

2. The planning and control of multi-limbed systems in field environments

In our previous work on the Force Workspace and Coordinated Jacobian Transpose Control we learned that, with a good system model and good knowledge of its environment, effective algorithms can be developed for task planning and real-time control of a multi-limbed system. However, such algorithms are based on analysis of the capabilities of the system and the nature of the environment at any given instant. The resulting analytical functions are also functions of the instantaneous posture with respect to its environment and task. These model-based methods do not lead to very effective methods for field robots operating in unstructured environments, such as the system shown schematically in Figure 3.

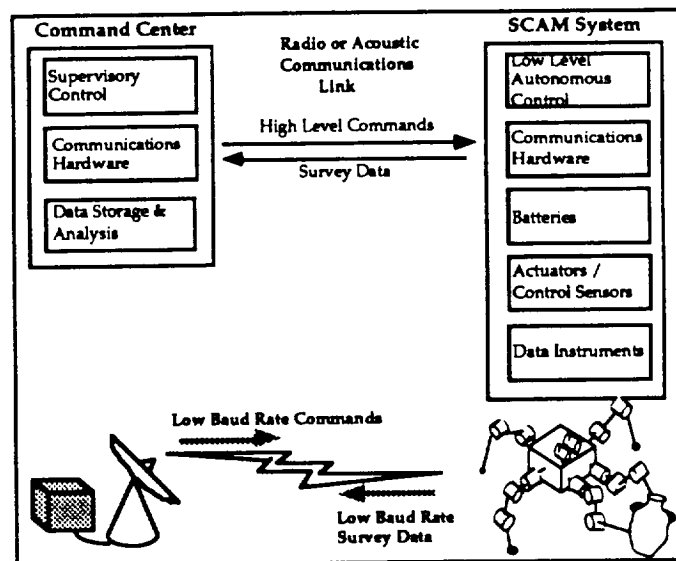


Figure 3. An Explorer Robot Concept

Model based methods are computationally intensive and require a great deal of sensing. Recently proposed behavior based algorithms, such as the highly promising subsumptive architecture, avoid nearly all analysis. Hence they are suitable for use by self-contained field systems with relatively low computational capabilities. Essentially, they function using a set of behaviors that are preprogrammed into the system's controller. These behaviors are generally formulated in an ad hoc manner, and they do not exploit our ability to understand the physical nature of these systems. The systems also often "try" actions that are physically unfeasible or not very "wise." Finally these methods rely on the programmer's judgment to establish the "best" set of behaviors. Hence they are at the other extreme of model based planning methods.

This phase of research would explore the blending of these two approaches to achieve the advantages of each, into what might be called *Model Based Behavior* (MBB) planning

and control. We would develop a behavior based planner that would exploit models representing what is known about the system, its environment and its instantaneous posture with respect to the environment and the task. However, the methods could rely on the robustness of behavior based control to fill in where the knowledge was incomplete. This would also permit the development of on-line procedures for creating behaviors so the systems could achieve best performance in a changing environment. Such performance issues as power efficiency and stability of stance will be considered. By providing a rational basis for the generation of behaviors for planning and control, it also would enable their software to be generated automatically. This automatic generation of software would enhance the ability to design modular field systems. The end objective of the research is being the development of methods for the rapid design and deployment of field systems, an essential capability for the successful commercial application of robotics.

3. The design of multi-limbed systems in field environments

The objective of this work would be the development of design paradigms, with a strong analytical basis, for new areas of robotics with both space and terrestrial applications. In this phase of the work we would continue to study the fundamental nature of multi-limbed systems in complex unstructured environments. The work would focus on how the performance capabilities are a function of the system's configuration and design parameters. As for planning and control algorithms, a strong underlying analytical basis for the system performance would permit rational design methods to be developed. This is an essential prerequisite to the development of a modular design approach, one using a defined set of components. A finite number of design modules and a well-defined set of performance capabilities would enable computer based search techniques, such as branch and bound, to be applied to the design (or assembly) of a system for a given mission. This would align with our objectives of developing methods to achieve rapid deployment of field robotic systems.

Our research in this area of planning, control and design of multi-limbed systems in unstructured field environments would be tested and demonstrated in connection with our work on the *USS Constitution*.

B. Experimental Studies

Our initial experimental studies will first focus on evaluating and validating our planning and control algorithms for flexible base robotic systems, such as the SPDM/SSRMS configuration. We will use our VES II system for these tests. Both our

Coupling Map (CM) based planning algorithms and our P-PED control algorithms will be tested in this work. These algorithms were largely successfully tested using the experiments carried out on the Martin Marietta testbed and using our Shaky I system. However these testbeds have the limitation that they are restricted to planar motions, and true spatial effects can not be considered. The use of the VES MOD II will overcome this limitation.

As discussed in Section III.A, we will also experimentally investigate the application of our Inferred Jacobian Transpose Control for flexible base robotic systems using the new constructed Shaky II Testbed. Shaky II will permit full spatial investigation for a dual arm system. The VES cannot be used for these tests since an important aspect of the testing is to determine if relatively easily strain measurements can be used to infer accurately the location of the manipulator's end-effector and in turn to compensate for base motions. This requires the use of a real supporting structure, rather than an emulated one.

In our early work the LIBRA system will be used to study experimentally our algorithms for control and planning the actions of multi-limbed systems. A prototype set of on-board electronics have been designed and built. During this proposed work the LIBRA will be modified to be entirely self-contained. This will provide the motivation to apply and verify our design and planning methods for systems without umbilicals, such as the Power Map approach for finding power-efficient behaviors and designs. This will expose us to a number of the hardware and software implementation issues that will be important to the design of the prototype systems that will be developed for the *USS Constitution*. Our planning, control and design methods for multi-limbed systems in unstructured field environments will ultimately be tested and demonstrated in connection with our work on the *USS Constitution*.

C. Technology Transfer

During the coming period, we would insure appropriate technology transfer of our previous research results by:

- Applying our methods to proposed flight development systems, in particular the INSTEP Program, the DOSS program and a Lunar surface vehicle application.

As part of this work we would consider how the performance of our methods is affected when applied to real systems, and extend and modify the methods as necessary. We will continue to work on the application of robotics to the restoration

and preservation of the *USS Constitution* as an appropriate dual use application, with potentially important historical and societal benefit.

IV. CONCLUSIONS

We believe that this MIT/Langley research program is widely recognized as a world leader in developing the fundamental enabling science for space robotics. We expect that, under this proposed three-year research program, we will continue to earn this reputation. More importantly, we believe that this proposed research will effectively contribute to NASA's future robotic systems meeting their mission objectives and will be a meaningful component in the education of our students.

V. THESES, PAPERS, LECTURES AND VISITING RESEARCHERS

Papers and theses written, presented or published during the current three year period (1991 to 1994) are listed in this section.

A. Student Theses

During this period, the program has given non-degree research opportunities to approximately 12 undergraduates under MIT's Undergraduate Research Opportunity Program (UROP). In addition, the following students who have contributed to this program, have completed their degrees and written the following theses:

1. Bachelors Theses

Mo, Patrick, "Experimental Performance of a Mobile Manipulator Resolved Rate Algorithm for Large Motion Control," Bachelors Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, May 1992.

Pomper, Brian, "The Integration of Force and Motion Planning: A Graphical Simulation of Gait Planning," Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, May 1992.

Russell, Charisse, "Gravity Compensation for a Space Manipulator: Estimating the Mass Properties of a PUMA 560," Bachelors Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA May, 1992.

Rowe, Patrick, "Endpoint Control of Elastically Mounted Robotic Systems: Simulation and Experimentation," Bachelors Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, May 1994.

2. Masters Theses

Madhani, Ackhil, "Design and Motion Planning of Robotic Systems Subject to Force and Friction Constraints," MS thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, August, 1991.

Gong, Youhong, "Design Analysis of a Stewart Platform for Vehicle Emulator Systems," MS thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, Jan., 1992.

Idris, Husni, "Real-Time Control of a Six Degree-of-Freedom Vehicle Emulation System, Masters Thesis, Depart. of Mechanical Engineering, MIT, Cambridge, MA, April, , 1992.

Müller, Uwe, "The Design of a Second Generation Experimental System for Studying Mobile Manipulators," Masters Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, June, 1992.

Baker, Jay, "Gravity Compensation for Experiments in Space Robotics," Masters Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, September, 1992

Argaez, Dalila, "An Analytical and Experimental Study of the Simultaneous Control of Motion and Force of a Climbing Robot," Masters Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, June, 1993.

Kuklinski, Andrew, "The Practical Implementation of an Experimental Tool for the Dynamic Interactions in Mobile Manipulator Systems," Masters Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, June, 1993.

Moore, Chantal, "The Design of Untethered Robotic Systems--An Experimental and Analytical Study of a Climbing Robot," Masters Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, September, 1993.

Sunada, Craig, "An Experimental Study of Coordinated Jacobian Transpose Control for Mobile Multi-limbed Robotic Systems," Masters Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, May, 1994

Corrigan, Thomas, "Emulating Micro-Gravity in Laboratory Studies of Space Robotics," Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, May, 1994.

3. Ph.D. Theses

Papadopoulos, E., "On the Dynamics and Control of Space Manipulators," Ph. D. Thesis, Department of Mechanical Engineering, MIT, Cambridge, Massachusetts, December, 1990.

Hootsmans, Norbert, "The Motion Control of Manipulators on Mobile Vehicles," Ph.D. Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, January, 1992.

Plumet, Frédéric, "Commande Dynamique et Placement de Taches Optimales pour Manipulateurs rapides," (Dynamic Control and Optimal Task Planning for Fast Manipulators"), Ph.D. Thesis, Robotics Laboratory of Paris, University of Paris VI, Paris, France, November, 1992.

Deck, Joseph, "Modeling of Flexible Spatial Machines With Clearance," Ph.D. Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, December, 1992.

Torres, Miguel, "Modelling, Path-Planning and Control of Space Manipulators: The Coupling Map Concept," Ph.D. Thesis, Department of Mechanical Engineering, MIT, Cambridge, MA, February, 1993.

B. Research Affiliates

During this period the following visiting researchers and researchers in residence have also contributed to our program:

Uwe Müller
Heidelberg University
Heidelberg Germany

Phillipe Bidaud
Laboratoire de Robotique de Paris
Paris, France

Bian, Zhene
Central South University of Technology
People's Republic of China

Antonella Semeraro
Tecnopolis—School for Advanced Studies in Industrial and Applied Mathematics,
Bari, Italy.

Sandra Brunettaas:
Tecnopolis—School for Advanced Studies in Industrial and Applied Mathematics,
Bari, Italy.

Attilio Pisoni
University of Ancona, Ancona, Italy.

Mavroidis, Constantinos
University of Paris IV
Paris, France

Yoshida, Kazuya
Tokyo Institute of Technology
Meguro, Tokyo 152, Japan

C. Period Technical and Professional Papers

During the current period the following papers have been published or accepted for publication in conferences proceedings or professional and scholarly journals.

1. Hootsmans, N. and Dubowsky, S., "The Control of Mobile Manipulators Including Vehicle Dynamic Characteristics," *Proceedings of the Fourth Topical Meeting on Robotics and Remote Systems*, February 24-28, 1991, Albuquerque, NM, pp. 461-470.
2. Dubowsky, S. and Torres, M.A., "Path Planning for Space Manipulators to Minimize Spacecraft Attitude Disturbance," *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, CA, April 7-12, 1991, Vol. 3, pp. 2522-2528.
3. Papadopoulos, E., and Dubowsky, S., "Coordinated Manipulator/Spacecraft Motion Control for Space Robotic Systems," *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, CA, April 7-12, 1991, Vol 2, pp. 1696-1701.
4. Hootsmans, N.A.M. and Dubowsky, S., "Large Motion Control of Mobile Manipulators Including Vehicle Suspension Characteristics," *Proceedings of the 1991 IEEE International Conference on Robotics and Automation*, Sacramento, CA, April 7-12, 1991, Vol. 3, pp. 2336-2341.

5. Papadopoulos, E. and Dubowsky, S., "Failure Recovery Control For Space Robotic Systems," *Proceedings of the 1991 American Control Conference*, Boston, MA, June 26-28, 1991, pp. (Invited).
6. Durfee, W.K., Idris, H.R. and Dubowsky, S., "Real-Time Control of the MIT Vehicle Emulation System," *Proceedings of the 1991 American Control Conference*, Boston, MA, June 26-28, 1991.
7. Dubowsky, S., Gu, P-Y, and Deck, J. F., "The Dynamic Analysis of Flexibility in Mobile Robotic Manipulator Systems," *The Eighth World Congress on the Theory of Machines and Mechanisms.*, August 26-31, 1991, Prague, Czechoslovakia, pp. Vol. 1, pp. 9-12. (Invited Plenary Paper.)
8. Papadopoulos, E., and Dubowsky, S. "On the Nature of Control Algorithms for Free Floating Space Manipulators," *IEEE Journal of Robotics and Automation*, Vol. 7, No. 6, December 1991, pp. 750-758.
9. Shiller, Z., and Dubowsky, S., "On Computing the Global Time Optimal Motions of Robotic Manipulators in the Presence of Obstacles," *IEEE Journal of Robotics and Automation*, Vol. 7, No. 6, December 1991, pp. 785-797.
10. Papadopoulos, E. and Dubowsky, S., "Dynamic Singularities in Free-Floating Space Manipulators," *ASME Journal of Dynamic Systems, Measurement and Control*, March 1993, Vol. 115, No. 1, pp. 44-52.
11. Dubowsky, S., "The Future Role of the Science of Mechanisms in Design," chapter 13, pp. 575-581, *The First Forty Years of Modern Kinematics*, Pub. John Wiley & Sons, Inc. A Tribute to Ferdinand Freudenstein, Arthur G. Erdman, Editor. Minneapolis/Brainerd, Minnesota, July 20-23, 1991.
12. Madhani, A. and Dubowsky, S., "Motion Planning of Mobile Multi-Limb Robotic Systems Subject to Force and Friction Constraints," *Proceedings 1992 IEEE International Conference on Robotics and Automation*, Nice, France, May 10-15, 1992, Vol. 1, pp. 233-239.
13. Hootsmans, N.A.M., Dubowsky, S., and Mo, P., "The Experimental Performance of a Mobile Manipulator Control Algorithm," *Proceedings 1992 IEEE International Conference on Robotics and Automation*, Nice, France, May 10-15, 1992, Vol. 3, pp. 1948-1954.
14. Madhani, A. and Dubowsky, S., "Planning Motions of Robotic Systems Subject to Force and Friction Constraints with an Application to a Robotic Climber," *Proceedings of IX CISM-IFTOMM Symposium on Theory and Practice of Robots and Manipulators* (ROMANSY '92), Udine, Italy, September 1-4, 1992.
15. Torres, M. and Dubowsky, S., "Minimizing Spacecraft Attitude Disturbances in Space Manipulator Systems," *AIAA Journal of Guidance, Control, and Dynamics*, Jul-Aug 1992, Vol. 15, No. 4, pp. 1010-1017.
16. Dubowsky S. and Papadopoulos, E., "The Kinematics, Dynamics and Control of Free-Flying and Free-Floating Space Robotic Systems," *Special Issue on Space Robotics, IEEE Transactions on Robotics and Automation*, Vol. 9, No. 5, October 1993, pp. 1-13. (Invited).
17. Dubowsky, S., Chapters 2 and 3 - *Space Robotics: Dynamics and Control*, Published by Kluwer Academic Publishers, Norwell, MA, 1993, Xu and Kanade - Editors.
18. Madhani, A. and Dubowsky, S., "Design and Motion Planning of Multi-Limb Robotic Systems: The Force Workspace Approach," *Proceedings of 1992 ASME Mechanisms Conference*, Scottsdale, AZ, Sept. 13-16, 1992. Also accepted to *ASME Journal of Mechanical Design*, March, 1993.
19. Deck, J. and Dubowsky, S., "On the Limitations of Predictions of the Dynamic Responses of Machines with Clearance Connections," *DE-Vol. 47, Flexible Mechanisms, Dynamics, and Analysis*, edited by Kinzel et al., pp. 461-469, *ASME Design Engineering Technical Conference*, Phoenix, AZ, Sept. 13-16, 1992. Also accepted for publication to the *ASME Journal of Mechanical Design*, 1994.
20. Hootsmans, N.A.M., Dubowsky, S., and Mo, P.Z., "Large Motion Control of an Experimental Manipulator with Limited Sensing," *Proceedings of 31st SICE Annual Conference*, Kumamoto, Japan, July 22-24, 1992, IS 4-5, pp. 983-986.

21. Torres, M.A. and Dubowsky, S., "Path Planning for Elastically Constrained Space Manipulator Systems," *Proceedings of 1993 IEEE International Conference on Robotics and Automation*, Atlanta, GA, May 2-7, 1993, Vol. 1, pp. 812-817.
22. Hootsmans, N.A.M., Dubowsky, S., and Mo, P.Z., "Experimental Verification of a Control Algorithm for a Manipulator with a Moving Vehicle Mechanism," *Mechanical Automation*, Vol. 25, No. 6, June, 1993, pp. 101-105 (in Japanese).
23. Kakizaki, T., Deck, J. F., and Dubowsky, S., "Modeling the Spatial Dynamics of Robotic Manipulators with Flexible Links and Joint Clearances," *ASME Journal of Mechanical Design*, December 1993, Vol. 115, No. 4, pp. 839-847.
24. Torres, M.A., Dubowsky, S., and Pisoni, A.C., "Path Planning for Elastically-Mounted Space Manipulators: Experimental Evaluation of the Coupling Map," *Proceedings of 1994 IEEE International Conference*, San Diego, CA, May 8-13, 1994.
25. Sunada, C., Argaez, D., Dubowsky, S. and Mavroidis, C., "A Coordinated Jacobian Transpose Control for Mobile Multi-Limbed Robotic Systems," *IEEE International Conference on Robotics and Automation*, San Diego, CA, May 8-13, 1994.
26. Dubowsky, S., Durfee, W., Corrigan, T., Kuklinski, A. and Müller, U., "A Laboratory Test Bed For Space Robotics: The VES Mod II," *IROS '94 IEEE/RSJ/GI International Conference on Intelligent Robots and Systems-Advanced Robotic Systems and the Real World*, September 12-16, 1994 in München, Germany.
27. Corrigan, T. and Dubowsky, S., "Emulating Micro-Gravity in Laboratory Studies of Space Robotics," *Proceedings of the 23rd ASME Mechanisms Conference*, MN, Sept. 1994. Also submitted for publication to *ASME Journal of Mechanical Design*.
28. Dubowsky, S., Durfee, W., Kuklinski, A., Muller, U., Paul, I., and Pennington, J., "The Design and Implementation of a Laboratory Test Bed for Space Robotics: The VES MOD II" *Proceedings of the 23rd ASME Mechanisms Conference*, MN, Sept. 1994. Also submitted for publication to *ASME Journal of Mechanical Design*.
29. Dubowsky, S., Moore, C. and Sunada, C., "On the Design and Task Planning of Power Efficient Field Robotic Systems," Submitted to the ANS 6th Topical Meeting on Robotics and Remote Systems, Monterey CA, Feb., 1995.
30. Mavroidis, C., Rowe, P., and Dubowsky, S. "Inferred Endpoint Control of Elastically Mounted Space Manipulator Systems," Submitted to the Third International Symposium on Artificial Intelligence, Robotics, and Automation for Space (i-SAIRAS 94), Jet Propulsion Laboratory, Pasadena, CA, October 18-20, 1994.

D. Invited Lectures and Seminars

During this period the following lectures and seminars have been given based on the results obtained in this research program :

May 1991, "Controlling Free-Flying Space Robotic Systems," Symposium International Europe - Etats-Unis, New Frontiers in Science and Engineering in a European Perspective, Paris, France. Organized by La Conférence des Grandes Ecoles, University of California-Berkeley, Massachusetts Institute of Technology.

October 1991, "On the Dynamics and Control of Mobile Telerobotic Manipulators in Unstructured Environments," Symposium on Telerobotics: Research and Applications, Sponsored by the Industrial Liaison Program, Massachusetts Institute of Technology, Cambridge, MA.

November 1991, "On the Planning of Force Controlled Motions in Mobile Manipulator Systems," Paris VI, Robotics Laboratory of Paris, Paris, France.

November 1991, "Research on Mobile Robotic Systems, Vision and Machine Dynamics—with Application to Nuclear Maintenance," Framatome (private industry), Paris, France, sponsored by MIT's Industrial Liaison Program.

June 1992, Space Robotics, Robotics Laboratory of Paris, Université Pierre et Marie Curie (Paris VI).

July 1992, "The Dynamics and Control of Mobile Robotic Systems," Framatome Corp., Paris, France, sponsored by MIT's Industrial Liaison Program.

July 1992, "The Dynamics and Control of Mobile Robotic Systems," Electricité de France, Groupe Teleoperation - Robotique,, Chatou Cedex, France, sponsored by MIT's Industrial Liaison Program.

July 1992, "Robotics Research," New Domains Department, Thomson-CSF Corp., Orsay Cedex, France, sponsored by MIT's Industrial Liaison Program.

July 1992 "Dynamic Modeling of Space Systems with Flexible Elements," Department Etudes et Productions, Schlumberger Corp., Clamart, France, sponsored by MIT's Industrial Liaison Program.

July 1992, Lecture series on "Kinematics, Dynamics, Control and Planning of Space Robotics Systems," Technopolis CSATA NOVUS ORTUS, SASIAM (School for Advanced Studies in Industrial and Applied Mathematics), Bari, Italy.

November 1992, "Force Workspace Planning for Robotics in Unstructured Environments," Research and Development, Intelligent Systems Group, Siemens Corp., Munich, Germany, sponsored by MIT's Industrial Liaison Program.

December 1992, "On the Dynamics and Control of Mobile Telerobotic Manipulators in Unstructured Environments," Department of Mechanical Engineering, University of California-Davis, Davis, CA.

December 1992, "On the Dynamics and Control of Mobile Telerobotic Manipulators in Unstructured Environments," Artificial Intelligence Laboratory, Stanford University, Stanford, CA.

December 1992, "On the Dynamics and Control of Mobile Telerobotic Manipulators in Unstructured Environments," Department of Mechanical Engineering, Naval Post-Graduate School, Monterrey, CA.

February 1993, "Design and Control of Mobile Robotic Systems for Unstructured Environments," Department of Mechanical Engineering and Applied Mechanics, sponsored by the URI Visiting Scholars Committee, University of Rhode Island, Kingston, RI.

May 1993, "Designing Robotic Systems for Field Environments," Engineering Department, Cambridge University, Cambridge, United Kingdom.

May 1993, "Control of Force and Motion in Mobile Robotic Systems," Department of Mechanical Engineering, Salford University, Salford, United Kingdom.

May 1993, "Designing Mechatronic Systems," Engineering Design Centre, Lancaster University, Lancaster, United Kingdom.

June-July 1993, Series of three seminars on "The Dynamics and Control of Space Robotic Manipulators," Robotics Laboratory of Paris, Université Pierre et Marie Curie (Paris VI).

October 25, 1993, "On the Dynamics and Control of Mobile Telerobotic Systems in Unstructured Environments," Center for Intelligent Machines, McGill University, Quebec, Canada.

November 11, 1993, "On the Dynamics and Control of Mobile Telerobotic Systems in Unstructured Environments," University of Pennsylvania, Dept. of ME and Applied Mechanics, Philadelphia, PA.

Appendix A: The Project Constitution

A Research Program on Robotic Systems to Assist in the Conservation, Restoration, and Preservation of Architectural and Archaeological Treasures



I. INTRODUCTION

The purpose of this document is to outline the motivation and activities of the of program called Project Constitution. The objective of this program is to develop the technology required for autonomous multi-limbed mobile robots in unstructured field environments.

Over the past decade, significant technological advancement has been made in this field of robotics at substantial costs by such agencies as NASA, NSF, the Department of Defense, and the Department of Energy [1-5], including work we have done [6-9]. Still, important technical developments are still required before such systems can be widely applied. The potential applications of this technology include environmental restoration, nuclear inspection, undersea maintenance and space exploration.

In this program we are considering these problems in the context of a new and exciting application area; robotic systems to assist in the conservation, restoration, and preservation of architectural and archaeological treasures. Among the tasks that the conservation community is called on to perform, a number could greatly benefit from the application of robotics. Some manual conservation work has resulted, unavoidably in the deterioration of the site. For example, conservation work on some large monuments has used scaffolding anchors installed in holes drilled into the monument itself. Some conservation tasks, such as detailed mappings, are very tedious. Many tasks are limited due to safety considerations. Indeed, some tasks that are of interest to the conservation community simply are now impossible or impractical to execute due to safety issues and access limitations. Finally, many conservation tasks are simply too expensive using current techniques. Robotics may be able to solve some of these problems, capitalizing on the technological developments made in recent years.

The work in this project would include a demonstration project on the *USS Constitution*, a historical treasure of the United States. During the past two years our group, the Mobile Robotic Manipulator Group at MIT, has held discussions with a number of individuals regarding the application of robotics to the conservation field. These individuals have included conservation scientists from the Getty Conservation Institute, conservators from several museums and monuments, and notably, the conservation staff of the USS Constitution -- Old Ironsides. Mr. Charles Deans, the Director of the Naval Historical Center, Boston Detachment, that includes the Constitution, and Mr.

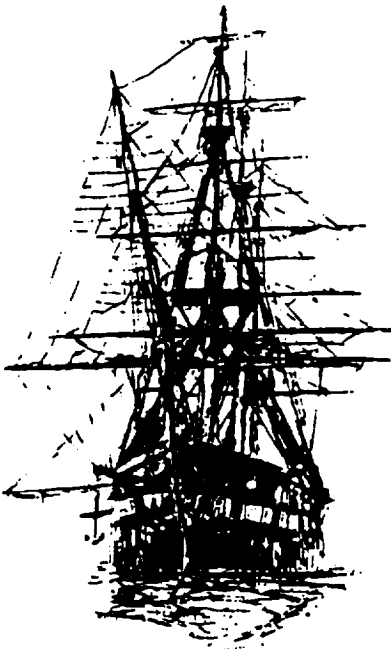
Donald Turner, the manager responsible for the preservation and conservation work on the ship, have been very helpful. As discussed below, it appears that the USS Constitution offers a number of excellent candidates for this research program's demonstration project.

This demonstration project has three major objectives. First, it will test the technology being developed, thereby uncovering any limitations in the technology that need to be addressed. Second, it is expected that this demonstration project would help promote the use of robotic technology in the preservation and conservation of historic monuments and artistic treasures. Third, it is anticipated that the system will be able to perform useful and meaningful conservation and preservation tasks on the Constitution.

This research program will require several years to complete. In the following sections we describe the work that has been done to date. The objective of this initial work was to define carefully the demonstration applications. This work has been carried out by members of the MIT team working with conservators and conservation scientists, including members of the Getty Conservation Institute and the Constitution conservation staff.

In defining these applications the expected capabilities of the technology has been considered, as well as the conservation needs. This work is currently focusing on the development of conceptual system designs and preliminary assessments of their required performance, their estimated cost and any technical risks. During the coming year a decision will be made to determine which concept will be designed, fabricated and tested.

As described below, we believe that this program will both enhance the capabilities of field robotics and have an important influence on the conservation and preservation of historical, architectural and artistic monuments and sites.



USS Constitution - "Old Ironsides"

II. A DESCRIPTION OF THE CONSTITUTION

The USS Constitution, perhaps better known as "Old Ironsides", is the oldest fully commissioned warship in the world, and a proud symbol of America's naval history. She first entered the water on October 21, 1797, and was on active war duty until May 15, 1815. She was never defeated in battle and has never been boarded, and earned her nickname of "Old Ironsides" during a battle where she took cannon shots at point blank range, yet the cannonballs merely bounced off of her sides. She is now berthed in Boston Harbor, and fires the National Salute on the Fourth of July. Several times

she has been threatened with destruction due to war damage or rotting of her timbers, but each time the US public demanded that she be restored. Oliver Wendell Holmes wrote a poem about her in 1830 that inspired the U.S. public to save the Constitution. To lose Old Ironsides would be to lose one of the most important parts of American heritage.



*Billet Head worn by the
Constitution, in the War of 1812*

She is constructed out of live oak, red cedar, white oak, pitch pine, and locust, with copper sheeting and fittings of copper and iron. Extraordinary craftsmanship went into her construction, and her conservation and preservation requires the same.

Congress has committed to preserving the Constitution in her 1812 configuration. This prevents the use of modern materials and composites to replace rotten wood. As with any wood exposed to the elements, her masts, decking, and timbers suffer from rot, and the stresses of supporting her 2200 tons causes the wood to warp over time. The USS

Constitution has needed major renovations on a number of occasions. Often, these major works required her to be in dry dock for years at a time. She is currently out of the water once again, this time for 20 months or more. Only constant inspection and active preservation efforts keep her in acceptable condition. During a normal year this involves a staff of approximately 20 professional craftsmen and a budget of \$2 million. This year's more major renovations involve around 70 craftsmen and a budget of approximately \$7 million.

III. ROBOTICS AND THE PRESERVATION OF THE USS CONSTITUTION

Robotics could make an important contribution to the preservation of the Constitution. Meetings between MIT faculty and graduate students and Charles Deans, Director of the Naval Historical Center, Boston Detachment, and his Production Manager Donald Turner have suggested several areas where robotics could make a major impact. One important thing that needs to be monitored on the Constitution is her hog. The weight of the ship tends to warp the wood of her keel, making it sag at the ends. This problem was exacerbated for the Constitution when several support beams were removed in a 19th century modification. If the hog becomes too large, the ship is in danger of irreparable damage. Excessive hog of 14 inches forced this year's renovation. The hog is currently measured once or twice a year using divers who carry a video camera and a scale to measure the distance from a cable stretched from bow to stern and the bottom of the keel. However, this is an expensive, time consuming, and potentially dangerous operation. Technology such as lasers and internal strain gauges have proved to be ineffectual or inaccurate. Articulated mobile robots, however, could replace the divers, making the hog measurement easier and faster and allowing more frequent monitoring of the hog. This suggestion was met with enthusiasm. If the hog is accurately known,

the ship's 190 tons of ballast could be shifted to minimize the warping. Computer models based on accurate data made under various conditions might even allow the hog to be corrected through ballast shifting without the need for costly drydocking which seriously detracts from the Constitution's educational and historical impact.



The Masts reach as high as 220 ft.

A second example of an important potential area for the application of robotics is the monitoring of the ship and its masts for rot. As a national treasure, the USS Constitution is visited by over half a million people each year. If one of the masts develops rot, a serious public safety hazard is posed. Several times masts have rotted and snapped in high winds. Fortunately, the masts have all been caught by the rigging and no fatalities have occurred. The masts are currently tested using a sonic testing unit which can detect rot in a cross section of the mast. However, the masts must be tested along their entire 220 foot height; only the lowest sections can be tested easily. The higher

sections require a crane or steeple jack. The dock crane, an unsightly yellow machine often referred to as 'the ship's fourth mast', takes weeks to perform a set of measurements, and the steeple jacks take even longer. Both are expensive and potentially dangerous. An articulated autonomous climbing robot could perform such a task much more easily, safely, cost effectively and frequently. Frequent testing could prevent the need for extensive repairs, since rot can be chemically halted if detected. The rigging also suffers from rot where large nests of crossing lines trap moisture. A moisture probe, once again carried by an articulated climbing robot, could check for excessive moisture and allow testing of the rigging that isn't attempted now.

Finally inside the hull, especially along the keel and under the ballast, there are spaces that need to be inspected for rot and treated. However the spaces are be hundreds of feet long and only a few inches high in places. They can be reached now, by workers, only every twenty years, when the ship goes into dry dock and the blast and hull planking is removed. Clearly, a "ferret" type of mobile multi-limbed robot capable of crawling through these spaces, carrying video camera, moisture probes and treatment devices would be a very useful system. Such a system is on of the prime candidates for early detailed study in the program.

IV THE SCIENTIFIC AND EDUCATIONAL COMPONENTS OF THE PROGRAM

This program will have important scientific and education benefits, as well as developing a system of potential practical use and demonstrating the application of robotics to the conservation community.

The basic engineering science portion of the program will focus on developing the technology that limits the performance of field robotic systems. The selection of the basic

problems to be studied will be motivated by the experience we gain from working on the Project Constitution. For example, it is likely that the system for the Constitution would be most effective if it were self-contained. Clearly, having to drag umbilical cables behind a field robot would diminish its effectiveness. Robotic systems without umbilicals will need to be power efficient. As a consequence, they would benefit from new actuator designs that are powerful, but efficient and lightweight. Another constraint for self-contained robotic systems is that they also will need to perform a great deal of the control and planning computation "on board," because they would be connected to fixed command and control stations by relatively low bandwidth communication channels. This will require the development of control algorithms which are not computationally intensive and can be run on small "on-board" computers.

The need to be both very power efficient and computationally efficient are just two of the technical challenges which face field robotic systems. Such challenges will lead to a number of important planning, control and design research problems. These research problems are the type that the robotics research community has been addressing for a number of years, and will form the basis for the thesis of the students working on the project. A complete description of our approaches and methods to solve such problems is beyond the scope of this brief program description and is available upon request.

We will test and validate the results obtained from these fundamental studies, first in computer simulations and then using experimental hardware. Much of the simulation work will be done using our previously developed software. The experimental hardware will be fabricated and tested in our mobile manipulator laboratory by our students. Clearly our students contributing to the project will gain invaluable design and research experience, while working on an interesting and exciting project with substantial societal value.

V. PROGRAM PLAN.

During this past year our work has focused on defining the application project that will be treated during the remainder of the multi-year program. It is expected that at the end of program, requiring approximately three years, a prototype field system will result which could prove the effectiveness of its technology under field conditions. The work the coming year will be divided into three activities, each lasting approximately four months.

Activity 1. Selection of the Conservation Application

Working with the Constitution's conservation staff, the Getty Conservation Institute, and other experts from the robotics research community, such as experts from NASA, a candidate conservation application for robotics on the Constitution will be selected. This selection will be ranked based on their utility to the conservation of the

Constitution and potential broader application. This work will include the development of a well-defined set of system performance goals. As part of this activity it is expected that an informal workshop will be held to review this selection.

Activity 2. Development of System Conceptual Designs and Design Selection

One or more design concepts will be generated for each of the selected demonstration projects. Preliminary engineering studies will be performed and the one identified with the highest probability of meeting their performance goals will be selected for further work.

Activity 3. Preliminary Design Study

In this activity a preliminary technical design will be performed, including supporting feasibility analysis. The results will include identification of any critical technical problems, and their risks, that need to be solved for a successful implementation of the design. System performance predictions will be made, including projected costs for a demonstration system.

Advisory Panel

As part of this program we would establish an advisory panel to review the work on a timely basis and provide guidance for the direction of the research. The panel would consist of approximately six individuals with technical or conservation backgrounds. Individuals from both within and outside of MIT would be invited to participate.

VI. CONCLUSIONS

We have briefly described the motivation and activities of the Project Constitution. In this research program we will study the problems of field robotics, including a demonstration project on the USS Constitution, a historical treasure of the United States. We believe that this program will both enhance the capabilities of field robotics and have an important influence on the conservation and preservation of historical, architectural and artistic monuments and sites.

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